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Effects of Energetic Particles on Minor Constituents of the Middle Atmosphere

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Both energetic protons and electrons can produce odd nitrogen compounds, NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HNO_4, $ClONO_2$), through interactions with the background atmosphere. The long lifetime of the NO_y family (up to several months in the middle atmosphere) as well as the NO_y species' significant influence on stratospheric ozone abundance make the charged particle increases of NO_y important. Galactic cosmic rays produce NO_y in the lower stratosphere, solar protons produce NO_y in the middle and upper stratosphere as well as the mesosphere, and relativistic electrons produce NO_y in the upper stratosphere and mesosphere, each affecting the NO_y middle atmosphere budget directly. Production of NO_y constituents by solar protons has been associated with an observed polar ozone depletion during and after the August 1972 solar proton event and a polar NO increase after the July 1982 solar proton event. Auroral electron and photoelectron production of NO_x (N, NO, NO_2) in the thermosphere and its subsequent transport downwards to the polar mesosphere and upper stratosphere is an important component of the NO_y budget in the middle atmosphere in the wintertime at high latitudes, e.g., the NO_2 enhancements measured by the limb infrared monitor of the stratosphere (LIMS) in the polar lower mesosphere and upper stratosphere during the winter of 1978–79 are thought to be caused by downward transport of NO_x.

1. Introduction

Energetic protons and electrons, which are focused by the earth's magnetic field to high geomagnetic latitudes, can influence the background middle atmosphere by perturbing the chemistry and constituents of polar and subpolar geodetic latitudes. These charged particles produce ions, radioactive isotopes, and HO_x (H, OH, HO_2) and NO_x (N, NO, NO_2) through interactions with the atmosphere. The ion production in the middle atmosphere results in the production of HO_x constituents after complicated ion chemistry (BRASSEUR and SOLOMON, 1984). A large number of radioactive isotopes are created by extremely energetic charged particles, e.g., galactic cosmic rays produce ^{14}C and ^{13}C which are useful in understanding the global carbon cycle (WARNECK, 1988).

The HO_x constituent production by solar protons has been associated with ozone decreases in the mesosphere and upper stratosphere (WEEKS *et al.*, 1972; SWIDER and KENESHEA, 1973; SWIDER *et al.*, 1978; FREDERICK, 1976; CRUTZEN and SOLOMON, 1980; MCPETERS *et al.*, 1981; SOLOMON *et al.*, 1981; THOMAS *et al.*, 1983; SOLOMON *et al.*, 1983a; SOLOMON *et al.*, 1983b; MCPETERS and JACKMAN, 1985; JACKMAN and MCPETERS, 1985; JACKMAN and MCPETERS, 1987). Substantial decreases in ozone associated with HO_x increases were observed during certain solar proton events, however, ozone levels recover within a couple of hours after the end of these particle events because of the short lifetime of HO_x species in the middle atmosphere.

The NO_x increases from charged particle precipitation result in an overall enhancement in odd nitrogen compounds, NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HNO_4, $ClONO_2$) in the middle atmosphere. Some of these effects on the middle atmosphere caused by NO_y species can be large and long-lived such as the August 1972 solar proton event disturbance (HEATH *et al.*, 1977; MCPETERS *et al.*, 1981; JACKMAN and MCPETERS, 1987), but these large perturbations are infrequent. Other charged particle effects on the middle atmospheric NO_y abundance are continuous but variable such as the perpetual flow of galactic cosmic rays (LEGRAND *et al.*, 1989). The long lifetimes of the NO_y family (up to months in the middle atmosphere) as well as the NO_y species' significant influence on stratospheric ozone abundance make the charged particle increases of NO_y important. Due to page limitations for this paper, only the impact of NO_y enhancements from charged particles will be discussed in this review.

The middle atmosphere NO_y abundance is influenced directly by galactic cosmic rays which produce NO_y in the lower stratosphere, solar protons which produce NO_y in the stratosphere as well as the mesosphere, and relativistic electrons which produce NO_y in the upper stratosphere and mesosphere. Auroral electron and photoelectron production of NO_y in the thermosphere and its subsequent transport downwards to the mesosphere and upper stratosphere is thought to be important to the NO_y budget in the middle atmosphere for the wintertime. Both model results and measurements of charged particle influences on NO_y and ozone in the middle atmosphere will be discussed.

2. Overview of Charged Particle Energy Deposition

A schematic diagram of the areas of influence by the various categories of charged particles and their associated products is shown in Fig. 1. This graph was created by modifying Fig. 2 from THORNE (1980). For a given energy, X-rays penetrate further than electrons and electrons penetrate further than protons (see Fig. 1). The X-rays (bremsstrahlung) result from the slowing down of the energetic electrons. The magnitude of

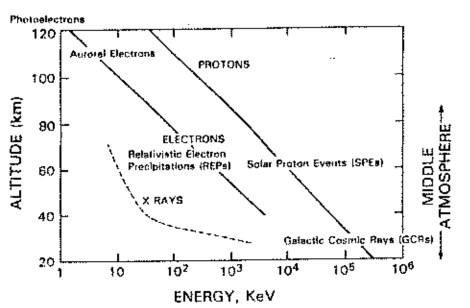

Fig. 1. Altitude of penetration for protons, electrons, and X-rays vertically incident at the top of the atmosphere as a function of particle energy (adapted from Fig. 2 of THORNE (1980)).

energy deposition by the X-rays is usually at least three orders of magnitude smaller than the energy deposition of the associated parent electrons (BERGER *et al.*, 1974).

Photoelectrons are produced by extreme ultraviolet (EUV) with energies up to a few hundred eV throughout the thermosphere. Primary electrons with energies less than 500 eV do not, in general, penetrate below 120 km (see Fig. 1). Photoelectrons are more similar to secondary electrons than primary electrons because these particles are produced by the in situ EUV ionization of background atmospheric constituents. The major region of atmospheric influence by the photoelectrons is the thermosphere (see upper left corner of Fig. 1). Since photoelectrons are produced by EUV, the only latitudinal dependence of the photoelectron energy deposition arises from changes in the solar zenith angle.

Some auroral electrons have energies capable of penetration to the mesosphere (electron energies <100 keV) with associated bremsstrahlung reaching the upper to middle stratosphere. The higher energy electron fluxes are indicated as relativistic electron precipitations (electron energies >100 keV) and are capable of depositing energy in the mesosphere and even the upper stratosphere with associated bremsstrahlung reaching the middle to lower stratosphere. Both auroral and relativistic electrons mainly deposit their energy in the subauroral region (geomagnetic latitudes between 60° and 70°) and their altitudes of deposition are indicated in Fig. 1.

Solar protons (energies <300 MeV) deposit their energy in the mesosphere and stratosphere and generally in the polar cap region (geomagnetic latitudes greater than 60°). Galactic cosmic rays deposit most of their energy in the lower stratosphere and upper troposphere at high latitudes; however, penetration of the higher energy galactic cosmic rays is possible all the way to tropical latitudes thus latitude dependent energy deposition distributions are required. The major altitudes of influence for solar proton events and galactic cosmic rays are indicated in Fig. 1.

3. Galactic Cosmic Ray Influence

The influence of galactic cosmic rays (GCRs) on the middle atmosphere has been studied over the past two decades (WARNECK, 1972; RUDERMAN and CHAMBERLAIN, 1975; NICOLET, 1975; JACKMAN *et al.*, 1980; THORNE, 1980; GARCIA *et al.*, 1984; LEGRAND *et al.*, 1989). GCRs produce odd nitrogen (NO_y) constituents through dissociation or dissociative ionization processes in which N_2 is converted to $N(^4S)$, $N(^2D)$, or N^+. Rapid chemistry is initiated after N_2 dissociation and most of the atomic nitrogen is rapidly converted to NO and NO_2. Since most of the particle energy deposited in the atmosphere goes into ionization processes, production rates of atomic nitrogen are generally described in comparison to the ion pair production rate. Values for atomic nitrogen produced per ion pair range from 0.33 (WARNECK, 1972) up to 1.27 (PORTER *et al.*, 1976). The PORTER *et al.* (1976) computations included a detailed energy deposition formulation for the relativistic speeds associated with many of the GCRs and are probably more reliable.

The major production of NO_y results from nitrous oxide oxidation ($N_2O + O(^1D) \rightarrow NO + NO$), thus the GCR-related production of NO_y must be compared to that background source in order to put its NO_y budget contribution into perspective. A comparison of the odd nitrogen production from the oxidation of N_2O rate for March (dashed line) and the mean GCR rate (solid line) is given in Fig. 2. The odd nitrogen production rate from the oxidation of N_2O was taken from a two-dimensional (2D) model involving a constrained computation

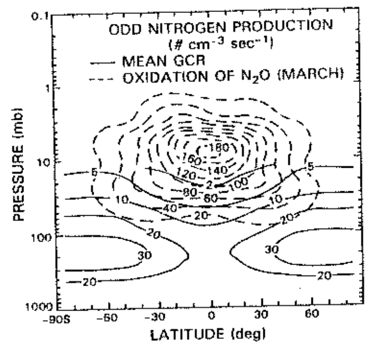

Fig. 2. Odd nitrogen production ($cm^{-3}sec^{-1}$) due to galactic cosmic rays (solid line, from Fig. 13 of JACKMAN *et al.* (1987)) and oxidation of nitrous oxide (dashed line, from Fig. 9 of JACKMAN *et al.* (1987)).

with stratospheric and mesospheric sounder (SAMS) N_2O data and solar backscatter ultraviolet (SBUV) O_3 data from the Nimbus 7 satellite (see Fig. 9a, JACKMAN *et al.*, 1987). The GCR mean odd nitrogen production rate was computed using the ion pair production rate given by NICOLET (1975) and assuming a production of 1.25 N atoms per ion pair (taken from Fig. 13, JACKMAN *et al.*, 1987).

The NO_y production is dominated in the middle and upper stratosphere by N_2O oxidation while the NO_y production is dominated in the lower stratosphere at the higher latitudes by the GCRs. Since the NO_y family has a lifetime of months in the middle and lower stratosphere, transport of NO_y created at higher altitudes and lower latitudes is significant and thus the GCR source of odd nitrogen has been computed to increase NO_y in the lower stratosphere at high latitudes by only about 10% (LEGRAND *et al.*, 1989; also our own 2D model computations). A solar cycle variation is apparent in the GCR flux with maximum flux during solar minimum and minimum flux during solar maximum.

The influence of GCRs on ozone over the 11-year solar cycle time period has been included in a 2D model computation of GARCIA *et al.* (1984). Since the effects of ultraviolet (UV) and auroral flux variation were also included in this computation, no quantitative changes from only the GCRs were reported. The Goddard Space Flight Center (GSFC) 2D model which extends from the ground to about 90 km (JACKMAN *et al.*, 1990) was used to investigate the influence of GCRs on NO_y abundance and ozone amounts. The minimum flux in GCRs (solar maximum) from a GSFC model computation allows about 0.25% more total ozone near the poles than computed during the maximum flux in GCRs (solar minimum). Predictions from the GSFC model indicated about 1% less total ozone at polar latitudes for a model run including GCRs compared to a model run not including GCRs. These model computations showed a seasonal as well as a strong latitudinal dependence with less than a 0.1% difference near the Equator between the two model runs just described.

4. Solar Proton Event Influence

Direct constituent change in the middle atmosphere by particles has only been documented in the case of solar proton events (SPEs). SPEs are sporadic with durations up to several days and have a solar cycle dependence such that more SPEs occur closer to solar maximum.

Polar ozone depletions associated with NO_y increases have been observed and modelled for the August 1972 SPE (CRUTZEN *et al.*, 1975; HEATH *et al.*, 1977; FABIAN *et al.*, 1979; MAEDA and HEATH, 1980/81; MCPETERS *et al.*, 1981; SOLOMON and CRUTZEN, 1981; REAGAN *et al.*, 1981; RUSCH *et al.*, 1981; JACKMAN and MCPETERS, 1987; JACKMAN *et al.*, 1990). The August 1972 SPE was one of the largest events in the past thirty years and substantial increases in NO_y have been computed to be associated with this event at polar latitudes in the middle to upper stratosphere (JACKMAN *et al.*, 1990).

Ozone decreases were observed by the backscatter ultraviolet (BUV) instrument aboard the Nimbus 4 satellite during the August 1972 SPE and are given in Fig. 3(a) (taken from Fig. 6a of JACKMAN *et al.*, 1990). Two-dimensional model computations of ozone decreases during this event are shown in Fig. 3(b) (taken from Fig. 7a of JACKMAN *et al.*, 1990) for easy measurement-model intercomparison. Both measurement and model indicate ozone depletions of over 20% in the upper stratosphere during the SPE with depletions of over 15% persisting for about two months after the SPE. The major difference between the measurement and the model results are the depletions in the upper stratosphere and lower

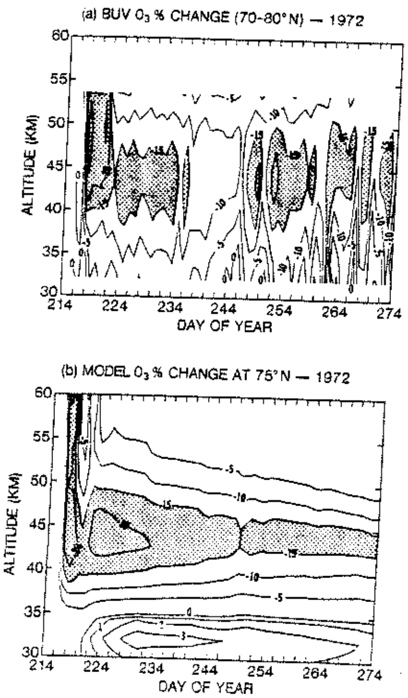

Fig. 3. Taken from Figs. 6(a) and 7(a) of JACKMAN *et al.*, Effect of solar proton events on the middle atmosphere during the past two solar cycles as computed using a two-dimensional model, *J. Geophys. Res.*, **95**, 7417–7428 (1990), copyright by the American Geophysical Union. Ozone depletion in 1972 due to the August 1972 solar proton event from (a) Nimbus 4 BUV measurements in the 70–80°N band and (b) 2D model predictions at 75°N. Shaded areas indicate ozone depletion greater than 15%.

mesosphere (near 50 km), where the model indicates a faster recovery than is indicated in the measurements.

The production of NO_y species by SPEs has been predicted since the mid-1970's (CRUTZEN *et al.*, 1975). The polar NO increase after the July 1982 SPE was inferred from the SBUV instrument to be about 6×10^{14} NO molecules cm^{-2} at polar latitudes (MCPETERS 1986), in good agreement with our calculated NO increase of 7×10^{14} NO molecules cm^{-2} in the polar cap assuming 1. 25 N atoms produced per ion pair (JACKMAN *et al.*, 1990).

5. Relativistic Electron Influence

Relativistic electron precipitations (REPs) have been proposed in the past 15 years to be important in contributing to the polar NO_y budget of the mesosphere and upper stratosphere (THORNE, 1977; THORNE, 1980; BAKER *et al.*, 1987; SHELDON *et al.*, 1988; BAKER *et al.*, 1988). The frequency and flux spectra of these REPs are still under discussion. BAKER *et al.* (1987) show evidence of large fluxes of relativistic electrons at geostationary orbit measured by the Spectrometer for Energetic Electrons (SEE) instrument on board spacecraft 1979–053 and 1982–019. REPs, which are actually depositing energy into the middle atmosphere, have been measured by instruments aboard sounding rockets (GOLDBERG *et al.*, 1984). These rocket measurements have typically indicated much smaller fluxes of relativistic electrons than measured by the SEE instrument.

A comparison of a typical energy deposition rate from a REP event measured by BAKER *et al.* (1987) (represented by the solid line) and the largest REP event studied in GOLDBERG *et al.* (1984) (represented by the small dashed line) is indicated in Fig. 4 (taken from a combination of Fig. 2 of BAKER *et al.* (1987) and the energy deposition curve of rocket 18.179 in Fig. 7 of GOLDBERG *et al.* (1984)). The energy deposition rates of EUV (dashed-dotted line) and GCRs (large dashed line) are shown for comparison in Fig. 4. In the lower mesosphere and upper stratosphere, the energy deposition rates are almost two orders of magnitude larger from the BAKER *et al.* (1987) REP event than from the GOLDBERG *et al.* (1984) REP event.

NO_y production rates from electrons with relativistic energies can be assumed to be

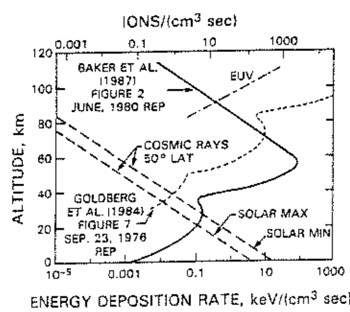

Fig. 4. Energy deposition due to relativistic electrons in June 1980 (solid line, from Fig. 2 of BAKER *et al.* (1987)), relativistic electrons on September 23, 1976 (small dashed line, from Fig. 7 of GOLDBERG *et al.* (1984)), extreme ultraviolet (dashed-dotted line, from Fig. 2 of BAKER *et al.* (1987)), and galactic cosmic rays (large dashed line, from Fig. 2 of BAKER *et al.* (1987)).

close to 1.25 N atoms per ion pair (PORTER *et al.*, 1976). REPs with the large fluxes measured by BAKER *et al.* (1987) could be an important influence on the NO_y budget in the lower mesospheric-upper stratospheric region at this NO_y production rate. However, REPs with the smaller fluxes measured by GOLDBERG *et al.* (1984) would cause a relatively insignificant change in NO_y amounts in the middle atmosphere at this NO_y production rate.

More work is necessary to determine which REP events are more typical of REPs which deposit their energy in the earth's atmosphere, the large fluxes measured at geostationary orbit or the relatively small fluxes measured by the sounding rockets.

6. Auroral Electron and Photoelectron Influence

The influence of auroral electrons and photoelectrons on the NO_y budget of the middle atmosphere through transport of NO_x from the thermosphere has been studied for the past two decades (STROBEL, 1971; MCCONNELL and MCELROY, 1973; BRASSEUR and NICOLET, 1973; JACKMAN *et al.*, 1980; SOLOMON, 1981; SOLOMON *et al.*, 1982; FREDERICK and ORSINI, 1982; GARCIA *et al.*, 1984; SOLOMON and GARCIA, 1984; RUSSELL *et al.*, 1984; BRASSEUR, 1984; LEGRAND *et al.*, 1989). Both auroral electrons and photoelectrons are capable of dissociating N_2 to form huge amounts of atomic nitrogen in the thermosphere. Transport of this NO_x to the mesosphere and upper stratosphere is possible, but certain conditions must be present.

The lifetime of NO_x in the thermosphere and mesosphere is short (less than a day) in the daytime and it is only during the long period of polar night at high latitudes, when several weeks of darkness is typical, that significant downward transport of NO_x is possible. SOLOMON *et al.* (1982) undertook a detailed 2D model study of the thermosphere—middle atmosphere coupling. They found enhancements of over an order of magnitude in the NO_x mixing ratio distribution in the upper mesosphere when auroral electron and photoelectron production of NO_x were included compared to a computation when both auroral electron and photoelectron production of NO_x were not included (compare Figs. 8 and 17 of SOLOMON *et*

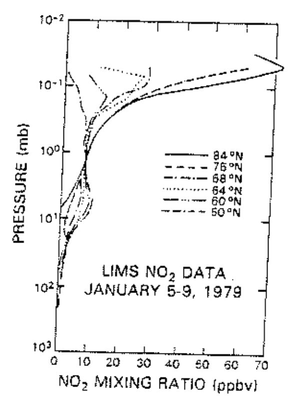

Fig. 5. Taken from Fig. 5 of RUSSELL *et al.*, The variability of stratospheric and mesospheric NO_2 in the polar winter night observed by LIMS, *J. Geophys. Res.*, **89**, 7267–7275 (1984), copyright by the American Geophysical Union. Zonal mean radiance averaged limb infrared monitor of the stratosphere NO_2 results for January 5–9, 1979.

al., 1982). These large enhancements of NO_x in the mesosphere caused by auroral electrons and photoelectrons are especially significant in the northern hemisphere which was most recently shrouded in polar night.

Measurements by the limb infrared monitor of the stratosphere (LIMS) of one significant species of NO_x, NO_2, have also indicated that large enhancements of NO_x in the mesosphere (above 1 mbar) are possible during polar night (RUSSELL *et al.*, 1984). Figure 5 (taken from Fig. 5 of RUSSELL *et al.* (1984)) indicates LIMS zonal mean radiance-averaged NO_2 results for the January 5–9, 1979 time period. Larger NO_2 values are indicated at higher latitudes, in qualitative agreement with model predictions. More study is required to determine how much of this mesospheric enhancement of NO_x is transported to lower altitudes, leading to increases in stratospheric NO_y.

7. Conclusions

Galactic cosmic rays cause small background solar cycle varying changes in the NO_y and ozone abundance in the lower stratosphere. Large solar proton events can cause substantial changes in the NO_y and ozone abundance in the middle and upper stratosphere, but tend to be sporadic. Relativistic electron precipitations could be important in modulating the NO_y abundance of the middle atmosphere but require more study and measurements of relativistic electrons in the earth's atmosphere. Auroral electrons and photoelectrons cause changes in NO_x amounts in the thermosphere which then can be transported to the mesosphere during polar night. More study is required to quantify the stratospheric NO_y change from auroral electron and photoelectron precipitation.

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